

# Sequestered uplifting and the pattern of soft supersymmetry breaking terms

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## Abstract

We examine the pattern of soft supersymmetry breaking terms in moduli stabilization, where an uplifting potential is provided by spontaneously broken supersymmetry in a generic sequestered sector. From stationary conditions, we derive the relation between moduli F-term vacuum expectation values which does not depend on the details of sequestered uplifting. This moduli F-term relation is crucial for identifying the dominant source of soft terms of visible fields.

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## I. INTRODUCTION

In string compactifications, the shape and size of the internal space are parameterized by moduli. Since the effective couplings of low energy theory are generically determined by moduli vacuum expectation values (VEVs), it is important to understand how the moduli are stabilized. It is naturally considered to add non-perturbative effects as a source of moduli fixing, and then the moduli can be fixed well by imposing supersymmetric stationary conditions. The corresponding vacuum energy is, however, negative for non-vanishing gravitino mass. In this case, a de-Sitter (dS) vacuum can be constructed via the uplifting mechanism [1, 2, 3, 4], where a supersymmetry (SUSY) breaking sector is introduced to provide positive energy to the scalar potential.

The SUSY breaking in uplifting sector would give rise to soft SUSY breaking terms, through effective cross-couplings between visible and uplifting sector fields, in the low energy lagrangian. Soft terms can involve flavor or CP violations which are already restricted by experiments. Hence, in order to avoid an additional source of flavor violations, the cross-couplings should be strongly suppressed unless the mediating interactions are flavor-blind. The suppression of such troublesome cross-couplings has led to the idea of sequestering [5]. It has been noticed that the sequestering is realized by spatially separated branes in strongly warped compactification [4, 6]. This geometrical sequestering can be also understood as the dual description of conformal sequestering [7] according to the AdS/CFT correspondence [8]. If sequestered from the visible sector, the uplifting sector would generate a dS vacuum without inducing additional soft terms of visible fields. This feature is phenomenologically desirable as the addition of uplifting effects causes no flavor violations.

In this paper, we wish to discuss the pattern of soft terms of visible fields within the framework of 4D supergravity, where an uplifting sector is sequestered from visible sector and spontaneous SUSY breaking takes place there. Particularly, we focus on how to identify the dominant source of visible soft terms. For this end, in the next section, we examine the general features of supergravity with a sequestered sector and present the relation between SUSY breaking quantities derived from stationary condition. It turns out that the dominant source of visible soft terms can be determined irrespectively of the detailed form of the sequestered sector. In section 3, using this property, it is found that moduli stabilization by non-perturbative effects naturally leads to mirage mediation [9, 10, 11, 12], while a dS

vacuum is achieved by the uplifting mechanism. Section 4 is the conclusion.

## II. SEQUESTERED UPLIFTING IN SUPERGRAVITY

In the flat spacetime background, the effective action for N=1 supergravity coupled to the gauge and matter superfields can be written in the rigid superspace [13]

$$\mathcal{S} = \int d^4x \sqrt{-g} \left[ \int d^2\theta d^2\bar{\theta} C \bar{C} (-3e^{-K/3}) + \left\{ \int d^2\theta \left( \frac{1}{4} f_a W^{a\alpha} W_\alpha^a + C^3 W \right) + \text{h.c.} \right\} \right], \quad (1)$$

where  $K$ ,  $W$  and  $f_a$  denote the Kähler potential, superpotential and gauge kinetic functions, while  $C = C_0 + \theta^2 F^C$  is the non-physical chiral compensator for super-Weyl invariance. The SUSY breaking effects originated from gravity are represented by the chiral compensator which involves the scalar auxiliary field of supergravity multiplet. Meanwhile, in the presence of radiative corrections, the super-Weyl invariance is maintained as a result of non-trivial dependence on  $C$  of running couplings. This implies that the F-term of chiral compensator generates soft terms at loop level [5, 14, 15]. Since soft terms always receive such contributions from anomaly mediation, it is quite important to know the relative importance of auxiliary components of SUSY breaking fields compared to  $F^C$ . In the Einstein frame where the graviton kinetic term is canonical, SUSY breaking quantities [14] are given by

$$\begin{aligned} F^I &= -e^{K/2} K^{I\bar{J}} (D_{\bar{J}} W)^*, & \frac{F^C}{C_0} &= \frac{1}{3} (\partial_I K) F^I + e^{K/2} W^*, \\ D^a &= -\frac{1}{\text{Re}(f_a)} \eta_a^I \partial_I K, \end{aligned} \quad (2)$$

where  $D_I W = \partial_I W + (\partial_I K) W$  is the Kähler covariant derivative of superpotential, and  $\eta_a^I$  denote the holomorphic Killing vectors for the infinitesimal gauge transformation of  $\Phi^I$ , i.e.  $\delta \Phi^I = \Lambda^a \eta_a^I(\Phi)$  for holomorphic  $\Lambda^a$ . Their VEVs are determined by minimizing the supergravity scalar potential  $V_{\text{tot}} = V_F + V_D$ ,

$$\begin{aligned} V_F &= e^K \left\{ K^{I\bar{J}} (D_I W) (D_{\bar{J}} W)^* - 3|W|^2 \right\} = K_{I\bar{J}} F^I F^{\bar{J}*} - 3|m_{3/2}|^2, \\ V_D &= \frac{1}{2} \text{Re}(f_a) D^a D^a, \end{aligned} \quad (3)$$

in which  $m_{3/2} = e^{K/2} W$  is the gravitino mass. In supergravity, supersymmetric field configurations satisfying  $D_I W = 0$  correspond to a stationary point of  $V_{\text{tot}}$ <sup>1</sup> if the superpotential

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<sup>1</sup> Due to the gauge invariance, the D-terms can be written in terms of Kähler covariant derivatives as  $D^a = -\frac{1}{\text{Re}(f_a)} \frac{\eta_a^I D_I W}{W}$ . Thus, it is obvious that the field configuration satisfying  $D_I W = 0$  leads to  $F^I = D^a = 0$  for  $W \neq 0$  [10].

does not vanish. However, the supersymmetric vacua have a negative vacuum energy, which should be compensated by SUSY breaking effects in order to achieve a phenomenologically viable dS or Minkowski vacuum.

In the presence of a sequestered sector, the effective supergravity is generically specified by Kähler and superpotential taking the form

$$\begin{aligned} K &= -3 \ln \Omega = -3 \ln \left( \Omega_{\text{vis}}(Q, \bar{Q}, T^i, \bar{T}^i) + \Omega_0(T^i, \bar{T}^i) + \Omega_{\text{seq}}(Z^\alpha, \bar{Z}^\alpha, \tilde{V}^a) \right), \\ W &= W_{\text{vis}}(Q, T^i) + W_0(T^i) + W_{\text{seq}}(Z^\alpha), \end{aligned} \quad (4)$$

where  $Q$  stands for the matter superfields in visible sector, and  $T^i$  denote the moduli whose VEVs determine the effective couplings of visible fields, while  $Z^\alpha$  and  $\tilde{V}^a$  are matter and vector superfields living in the sequestered sector respectively. In the superconformal frame, soft terms of visible fields are generated through effective cross-couplings between the visible and SUSY breaking fields [5]. From the above sequestered structure, however, it is manifest that the fields in sequestered sector do not have cross-couplings with other sector fields in the superconformal frame lagrangian (1). Hence the auxiliary components of  $Z^\alpha$  and  $\tilde{V}^a$  are irrelevant to visible soft terms, but have uplifting effects which would be necessary to realize a dS vacuum. Despite the absence of cross-couplings with other sector fields, the sequestered sector still influences the moduli configuration minimizing supergravity scalar potential through gravitational effects. This can be understood from that the chiral compensator couples to any operator in Kähler and superpotential. Indeed, the equation of motion for moduli  $T^i$  is generally not decoupled from the sequestered sector if supersymmetry is broken, though the supersymmetric stationary condition corresponds simply to  $D_i W = D_\alpha W = 0$ . For the study of SUSY breaking, one needs to know the VEV of SUSY breaking quantities rather than the field configuration itself at a vacuum. In this view, it is worthwhile to rephrase the stationary conditions in terms of auxiliary components

$$\begin{aligned} \partial_I V_F &= -2 \frac{\partial_I \Omega}{\Omega} V_F - \left( \frac{\partial_I \partial_J W}{W} F^J + 2 \frac{\partial_I W}{W} \frac{F^C}{C_0} \right) m_{3/2} \\ &\quad + 3 \frac{\partial_I \partial_J \partial_{\bar{L}} \Omega}{\Omega} F^J F^{L*} + 3 \frac{\partial_I \partial_J \Omega}{\Omega} F^J \left( \frac{F^C}{C_0} \right)^*, \\ \partial_I V_D &= - \left( \partial_I \ln(\text{Re}(\tilde{f}_a)) + 2 \frac{\partial_I \Omega}{\Omega} \right) V_D + 3 \frac{\tilde{\eta}_a^{J*} \partial_I \partial_{\bar{J}} \Omega}{\Omega} \tilde{D}^a, \end{aligned} \quad (5)$$

where  $I = \{i, \alpha\}$ ,  $V_D$  is the D-term scalar potential for  $\tilde{V}^a$ , and we have chosen the Einstein frame condition. For the gauge interactions in sequestered sector, the associated gauge

couplings have no dependence on moduli  $T^i$  and only the matter superfields living there are charged under the gauge group:

$$\tilde{f}_a = (T^i\text{-independent function}), \quad \tilde{\eta}_a^i = 0, \quad \tilde{\eta}_a^\alpha = \tilde{\eta}_a^\alpha(Z^\beta), \quad (6)$$

where  $\tilde{f}_a$  and  $\tilde{\eta}_a^I$  are the gauge kinetic function and holomorphic Killing vectors of sequestered sector gauge group, respectively. The sequestering therefore leads to that, written in terms of auxiliary components, the stationary conditions have the decoupled structure. Concretely, from  $\partial_i V_{\text{tot}} = \partial_i(V_F + V_D) = 0$ , the sequestered structure (4) results in the relation between moduli F-term VEVs

$$\frac{1}{3} \frac{\partial_i \partial_j W_0}{W} \hat{F}^j + \frac{2}{3} \frac{\partial_i W_0}{W} \hat{F}^C - \frac{\partial_i \partial_j \partial_k \Omega_0}{\Omega} \hat{F}^j \hat{F}^{k*} - \frac{\partial_i \partial_j \Omega_0}{\Omega} \hat{F}^j \hat{F}^{C*} = 0, \quad (7)$$

at a non-supersymmetric minimum of scalar potential with vanishing vacuum energy density  $V_{\text{tot}} = 0$ , where  $\hat{F}^{i,C}$  are F-components rescaled by the gravitino mass

$$\hat{F}^i \equiv \frac{F^i}{m_{3/2}^*}, \quad \hat{F}^C \equiv \frac{1}{m_{3/2}^*} \frac{F^C}{C_0}. \quad (8)$$

It should be noted that the moduli F-term relation (7) derived from stationary condition does not depend on the detailed structure of sequestered sector,  $\Omega_{\text{seq}}$  and  $W_{\text{seq}}$ . Since soft terms of visible fields are generated by  $F^i$  and  $F^C$ , the insensitivity of moduli F-term relation to the sequestered sector physics is crucial for identifying the dominant source of soft terms in the visible sector. The relation (7) would allow us to determine, without a detailed information about the sequestered sector, the relative importance of moduli mediation compared to the anomaly mediation which is always present in supergravity. In the next section, by using this relation between moduli F-term VEVs, we will examine the pattern of soft terms in generic scenario where the moduli are stabilized by adding non-perturbative effects.

For the sequestered uplifting scenario, uplifting procedure can be also described within an effective lagrangian that is obtained by integrating out the sequestered sector. Then, as constructed from the underlying theory (4), the effective theory should reproduce the moduli F-term relation (7) which is insensitive to the sequestered sector physics. The effects of sequestered sector fields are encoded in constant operators appearing in the resultant effective lagrangian

$$\begin{aligned} \mathcal{L}_{\text{eff}} = & \int d^2\theta d^2\bar{\theta} C \bar{C} \left( -3\Omega_0(T^i, \bar{T}^i) + P_0 + \bar{\theta}^2 \frac{C^2}{C} P_1 + \theta^2 \frac{\bar{C}^2}{C} P_1^* + \theta^2 \bar{\theta}^2 C \bar{C} P_2 \right) \\ & + \left\{ \int d^2\theta C^3 \left( W_0(T^i) + H_0 + \theta^2 \frac{\bar{C}^2}{C} H_1 \right) + \text{h.c.} \right\}, \end{aligned} \quad (9)$$

where spurion operators  $P_{1,2}$  and  $H_1$  represent the spontaneous SUSY breaking effects in sequestered sector, and their  $C$ -dependence is determined from the fact that the combination  $\theta^2 \bar{C}^2 / C$  is invariant under the global super-Weyl transformations. The operators  $P_{0,1,2}$  and  $H_{0,1}$  are  $T^i$ -independent constants because they are originated from the sequestered sector physics which is completely decoupled in the absence of gravitational effects. Hence, by appropriate redefinition of Kähler and superpotential, the effective lagrangian is written as

$$\mathcal{L}_{\text{eff}} = \int d^2\theta d^2\bar{\theta} C \bar{C} \left( -3\Omega(T^i, \bar{T}^i) - \theta^2 \bar{\theta}^2 C \bar{C} \mathcal{P}_{\text{lift}} \right) + \left\{ \int d^2\theta C^3 W(T^i) + \text{h.c.} \right\}, \quad (10)$$

in which the simple constant shifts of Kähler and superpotential have been taken into account

$$\Omega(T^i, \bar{T}^i) = \Omega_0(T^i, \bar{T}^i) - \frac{1}{3}P_0 \quad \text{and} \quad W(T^i) = W_0(T^i) + H_0 + P_1, \quad (11)$$

whereas the SUSY breaking effects by  $Z^\alpha$  and  $\tilde{V}^a$  are encoded in a D-type spurion operator

$$\mathcal{P}_{\text{lift}} = -P_2 - H_1 - H_1^*, \quad (12)$$

which appears basically when the F-term of sequestered matter fields develops a VEV, as the D-terms vanish if  $D_\alpha W = 0$  for all  $Z^\alpha$ . We note that, in the effective action, this spurion operator  $\mathcal{P}_{\text{lift}}$  mimics explicit SUSY breaking in a sequestered sector and provides a KKLT-type uplifting potential<sup>2</sup> given by

$$V_{\text{lift}} = e^{2K/3} \mathcal{P}_{\text{lift}}, \quad (13)$$

in the Einstein frame. For sequestered uplifting models with spontaneously broken SUSY, the moduli stabilization is therefore expected to have qualitatively same features as those in the KKLT scenario [1, 9, 10]. Including the uplifting potential (13), the vacuum configuration is now determined by solving  $\partial_i V_{\text{tot}} = \partial_i (V_F + V_{\text{lift}}) = 0$  where

$$\partial_i V_{\text{lift}} = -2 \frac{\partial_i \Omega}{\Omega} V_{\text{lift}}, \quad (14)$$

from which it is straightforward to obtain the same result for moduli F-term VEVs as (7) for vanishing vacuum energy,  $V_{\text{tot}} = V_F + V_{\text{lift}} = 0$ . The moduli F-term relation remains

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<sup>2</sup> In the KKLT flux compactification [1], an anti-brane is stabilized at the end of a warped throat, while the visible brane is supposed to be located at a region where the warping is negligible. The sequestering is then achieved for the spatially separated two branes through the warping, while uplifting potential is provided by explicit SUSY breaking on the anti-brane.

unmodified in the effective theory, as deduced from the fact that it is the consequence of full theory (4) and insensitive to the sequestered sector physics. Therefore, the SUSY breaking effects producing visible soft terms can be studied consistently by using the relation (7) in the effective theory (10), where the spontaneous SUSY breaking effects from sequestered sector are represented by a KKLT-type uplifting operator  $\mathcal{P}_{\text{lift}}$ .

### III. MODULI STABILIZATION

Non-perturbative effects, such as gaugino condensations [16], are considered as natural sources of moduli stabilization. In this section, including a sequestered sector, we discuss the pattern of soft terms in generic scenario where the moduli  $T^i$  are fixed by adding non-perturbative corrections to superpotential

$$W_0(T^i) = \sum_i A_i e^{-a_i T^i}, \quad (15)$$

where  $A_i = \mathcal{O}(1)$  in the unit with  $M_{Pl} = 1$ , and moduli are defined through the exponent. Provided that the Kähler potential for moduli  $T^i$  and its derivatives do not introduce hierarchically large numbers, the vanishing vacuum energy forces moduli F-terms to be at most of order of gravitino mass

$$\left| \frac{1}{m_{3/2}^*} \frac{F^i}{T^i} \right| \leq \mathcal{O}(1). \quad (16)$$

Furthermore, in order for supersymmetry to resolve the hierarchy problem, soft parameters have to be of TeV scale [17]. Since soft terms of visible fields are induced by moduli and anomaly mediations, the low energy SUSY requires F-term VEVs to satisfy

$$\left| \frac{1}{4\pi^2} \frac{F^C}{C_0} \right| + \sum_i \left| \frac{F^i}{T^i} \right| = \mathcal{O}(1) \text{ TeV}, \quad (17)$$

where we have used the fact that anomaly mediated contributions are suppressed by a loop factor. As long as the non-perturbative superpotential is the main source of moduli fixing, the associated moduli would be fixed according to  $A_i e^{-a_i T^i} \sim W$ . This implies  $\langle a_i T^i \rangle \approx \ln(M_{Pl}/m_{3/2}) \gg 1$ , because the moduli appear non-perturbatively in the superpotential. Hence, combined with the constraints on F-terms (16) and (17), the moduli F-term relation (7) gives

$$\frac{F^i}{T^i} \simeq \frac{2}{a_i T^i} \frac{F^C}{C_0} \approx \frac{2}{\ln(M_{Pl}/m_{3/2})} \frac{F^C}{C_0} \quad \text{with} \quad m_{3/2} \geq \mathcal{O}(1) \text{ TeV} \quad (18)$$

at a non-supersymmetric minimum with vanishing vacuum energy. We stress that the above result does not depend on the detailed form of sequestered sector,  $\Omega_{\text{seq}}$  and  $W_{\text{seq}}$ . If there are no SUSY breaking fields other than  $T^i$ , the moduli F-term VEVs are found to be  $F^i/T^i = \mathcal{O}(m_{3/2}/\ln(M_{Pl}/m_{3/2}))$  from (2) and (18), and thus are too small to cancel the negative vacuum energy of  $\mathcal{O}(m_{3/2}^2 M_{Pl}^2)$  in supergravity potential. This indicates that the uplifting effects from sequestered sector are responsible for the construction of a dS vacuum with nearly vanishing cosmological constant. It should be also noted that, owing to the suppression of moduli F-terms compared to  $F^C$  (18), the moduli mediation would give comparable contributions to soft terms as the loop-induced anomaly mediation. Consequently, the soft terms of visible fields are predicted to take the pattern of mirage mediation [9, 10, 11, 12] at low energies. In the sequestered uplifting scenario with spontaneously broken SUSY, mirage mediation is a natural consequence of non-perturbative moduli stabilization where the moduli appear non-perturbatively in superpotential. Moreover, the source of uplifting effects can be regarded as KKLT-like explicit SUSY breaking when the sequestered sector is integrated out. These features can be understood essentially from the fact that the moduli F-term relation (7) is insensitive to the sequestered sector physics.

To see the phenomenological aspects, we consider a simple case with a single Kähler modulus  $T$ . In the presence of a sequestered sector, the effective supergravity action is described by

$$K = -3 \ln \left( T + \bar{T} + \Omega_{\text{seq}}(Z^\alpha, \bar{Z}^\alpha, \tilde{V}^a) \right), \quad W = A e^{-aT} + W_{\text{seq}}(Z^\alpha), \quad (19)$$

where the non-perturbative superpotential is added to stabilize  $T$ , and  $A = \mathcal{O}(1)$ . Applying the relation (7) to this model, the VEV of modulus F-term is found to be exactly given by

$$\frac{F^T}{T} = -\frac{2}{T} \frac{\partial_T W}{\partial_T^2 W} \frac{F^C}{C_0} = \frac{2}{aT} \frac{F^C}{C_0}, \quad (20)$$

which is totally independent of the detailed structure of sequestered sector. Here the sequestered uplifting potential is adjusted to get a vanishing vacuum energy density. Due to the suppression of modulus F-term, the low energy values of soft parameters are expected to take the pattern of mirage mediation, where the mirage messenger scale [11] is determined by the ratio between modulus and anomaly mediations. The mirage messenger scale does not correspond to a physical threshold scale. Its appearance reflects the fact that the anomaly mediated contribution cancels precisely the renormalization-group evolved part of

soft parameters. Since the non-perturbative superpotential is supposed to be responsible for the stabilization of  $T$ , the modulus would have a VEV as  $\langle aT \rangle \approx \ln(M_{Pl}/m_{3/2})$ . Using this property for non-perturbative moduli stabilization, the mirage messenger scale is then estimated easily from (20), irrespectively of the detailed form of sequestered uplifting. Mirage mediation models can naturally avoid the SUSY CP and flavor problems as a consequence of approximate scaling and axionic shift symmetries [18, 19, 20]. It has been also noticed that the mirage mediation has a distinctive pattern of low energy soft parameters and interesting phenomenological implications [11, 12].

#### IV. CONCLUSION

We have studied the pattern of soft terms in the generic scenario of moduli stabilization, where a dS vacuum is constructed by combining a sequestered sector. Fields in the sequestered sector give contributions to spontaneous SUSY breaking, which achieve uplifting effects. The cosmological constant can be then adjusted to be arbitrarily small. In this framework, the addition of uplifting sector causes no flavor violations because the sequestering forbids cross-couplings between the visible and uplifting fields.

In supergravity, the moduli configuration minimizing scalar potential is generally affected by the sequestered sector through gravitational effects. Nonetheless, written in terms of SUSY breaking quantities, stationary conditions are found to have the decoupled structure. As a result, we obtain the relation between moduli F-term VEVs which does not depend on the detailed form of sequestered uplifting. This relation is crucial for determining the relative importance of moduli mediation compared to anomaly mediation which is always present in supergravity. For the study of phenomenological aspects, it is important to know the dominant source of soft terms of visible fields.

It is natural to add non-perturbative effects as a source of moduli fixing. Then, from the moduli F-term relation, it is found that moduli stabilization by non-perturbative superpotential naturally leads to mirage mediation, while a dS vacuum is constructed via the sequestered uplifting. The qualitative features are same as those in the KKLT scenario. These results can be understood from the fact that the moduli F-term relation is insensitive to the sequestered sector physics, and a KKLT-type uplifting potential arises in the effective theory when the sequestered sector is integrated out.

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